Grid Integration of Distributed Wind Generation: A Markovian and Interval Approach

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Introduction

- This work develops a synergistic combination of Markovian and interval optimization for unit commitment problems with wind generation and transmission
- Motivation: Important to accommodate high penetration of wind
  - DOE's goal: 20% wind by 2030
  - Obama's goal: 80% clean energy by 2035
  - In Spain, an unprecedented decrease in wind generation in Feb. 2012 is equivalent to the sudden down of 6 nuclear plants (4 is not unusual)
  - Texas Emergency Electric Curtailment Plan is called on in Feb. 2008
- Difficulties:
  - Intermittent/uncertain nature of wind generation
    - Cannot be dispatched as conventional units
    - Large uncertainty: Mean Absolute Error (normalized over capacity) of day-ahead wind power forecast: 15%~20%
  - Complicated structures of transmission networks
  - Computational complexity: NP hard problems

Literature Review

- Stochastic programming
  - Modeling wind generation – Representative scenarios
  - To minimize the expected cost over scenarios
  - Difficult to choose an appropriate number of scenarios to balance computational complexity and solution feasibility
- Robust optimization
  - Uncertainties modeled by an uncertainty set w/o probabilities
  - To optimize against the worst-case realization
  - Min Max conservative and computationally challenging
- Pure interval optimization [1]
  - Modeling wind generation – Closed intervals w/o probabilities
  - Capturing the bounds of uncertain inputs in different types of constraints, and making decisions feasible for these bounds
  - System demand constraints: As long as min. and max. wind realizations are feasible, other realizations within them will be feasible
    - E.g., wind farm 1 outputs [10 MW, 40 MW], and wind farm 2 [20 MW, 50 MW]. Total wind generation = [30 MW, 90 MW].
    - System demand = 200 MW. Net system demand = [110 MW, 170 MW]
    - If a set of committed units with p_i^{min} and p_i^{max} can meet the 110 MW and 170 MW, can it satisfy possible demand at 140 MW?
  - Transmission capacity constraints: |Power flow| $\le f_l^{max}$
    - A line flow is a linear combination of nodal injections weighted by generation shift factors (GSFs can be + or -)

$$f_l(t) = \sum_i a_l^i \left(p_i^I(t) + p_i^W(t) - p_i^L(t) \right), \forall l, \forall t \qquad (1)$$

    - "Passively" capture bounds of uncertain inputs

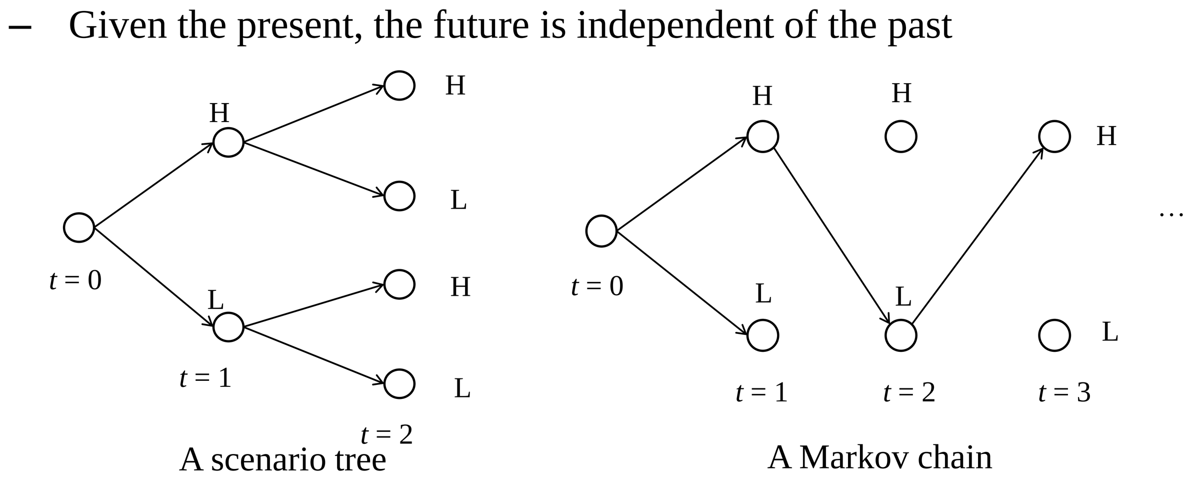
$$\sum_i a_l^i p_i(t) \le f_l^{\max} - \max\left[\sum_i a_l^i \left(p_i^W(t) - p_i^L(t) \right) \right], \forall l, \forall t \qquad (2)$$

Pre-computed based on interval arithmetic

  - Objective function: To minimize the cost of the expected realization
  - Linear and efficient via interval arithmetic; conservative

Previous Work - Markovian Optimization w/o Transmission [2]

- Model aggregated wind generation – A Markov chain
  - Given the present, the future is independent of the past



A scenario tree — N^T possible scenarios at one node

A Markov chain — $T{\cdot}N$ possible states at one node

  - Advantage: State at a time instant summarizes the information of all previous instants in a probabilistic sense for reduced complexity
- Stochastic UC depends on states instead of scenarios

Markovian and Interval Unit Commitment

- Wind model considering transmission constraints
  - With congestion, wind generation cannot be aggregated together
  - Wind states for farms at different nodes may not be the same
    - Nearby wind farms: Generation aggregated
    - Wind farms far apart: States assumed independent
  - A Markov chain per node
  - With I wind nodes (Markov chains): N^I possible global states at time t
    - *Curse of dimensionality!*

Key idea: Markov + interval-based optimization

- Markovian analysis to depend on local states; interval analysis to manage extreme combinations of non-local states
  - Local state: Wind generation state at the node under consideration (will be extended into zonal state in future work)
- Physical infrastructure supporting this idea: Wind-diesel system
- How to combine two distinct approaches? Divide the generation (dispatch decision) of a conventional unit into two components
  - *Markovian component* depends on the local state n_i

$$x_i(t) p_i^{\min} \le \boxed{p_{i,n_i}^M(t)} + \boxed{p_{i,\bar{n}_i}^I(t)} \le x_i(t) p_i^{\max}, \forall i, \forall t, \forall n_i, \forall \bar{n}_i \qquad (3)$$

  - *Interval component* manages extreme combinations of non-local states
- Constraints innovatively formulated to guarantee solution feasibility for all realizations without much complexity
- The effective use of local wind states alleviates the over-conservativeness of interval optimization

- System demand constraints
  - Based on interval optimization [1]: As long as min. and max. global states are feasible, all other realizations within them will be feasible

$$\sum_i \left(p_{i,\min n_i}^M(t) + p_{i,m_i}^I(t) \right) = \sum_j \left(p_i^L(t) - p_{i,\min n_i}^W(t) \right), \forall t \qquad (4)$$

The minimum local state at node i

The minimum combination of non-local states (where other nodes are at their minimum possible states)

$$\sum_i \left(p_{i,\max n_i}^M(t) + p_{i,M_i}^I(t) \right) = \sum_j \left(p_i^L(t) - p_{i,\max n_i}^W(t) \right), \forall t \qquad (5)$$

- Transmission capacity constraints: |Power flow| $\le f_l^{max}$
  - Flexibility of local conventional generation used to shrink ranges of RHS

$$\sum_i a_l^i p_i^I(t) \le f_l^{\max} - \max\left[\sum_i a_l^i \left(p_{i,n_i}^W(t) + p_{i,n_i}^M - p_i^L(t) \right) \right], \forall l, \forall t \qquad (6)$$

Markovian nodal injection (containing decision variables) $\equiv P_{i,n_i}^M(t)$

- Ramp rate constraints
  - Required for possible local states, local state transitions, $p_{i,m_i}^I(t)$, and $p_{i,M_i}^I(t)$
- The objective function: To approximate the expected cost w/o much complexity
  - A weighted sum of extreme realizations and the expected realization

$$\min \sum_{t=1}^{T} \sum_{i=1}^{I} \left\{ \sum_{n_i=1}^{Ni} \left[w_{n_i,m_i}(t) C_i\left(p_{i,n_i}^M(t) + p_{i,m_i}^I(t) \right) + w_{n_i,M_i}(t) C_i\left(p_{i,n_i}^M(t) + p_{i,M_i}^I(t) \right) \right] \right.$$
$$\left. w_E(t) C_i\left(p_{i,E}(t) \right) + u_i(t) S_i + x_i(t) S_i^{NL} \right\} \qquad (7)$$

Weights adding up to 1

- A non-linear MIP formulation
  - Non-linearity lies in max/min (negative flow direction) operations in (6)

Solution Methodology – Branch-and-cut

- Max/Min operations transformed into a linear form
  - *Idea:* Analyze the monotonicity of Markovian nodal injections w.r.t. local states, then select indices of local states w/o optimization
  - *The Monotonicity Conjecture*: The local state with lower wind generation provides less or equal Markovian nodal injection at the optimum, i.e.,

$$P_{i,n_i-1}^M(t) \le P_{i,n_i}^M(t), \forall i, \forall t, \forall n_i, \forall (n_i - 1) \in \{ n_i - 1 \mid \varphi_{n_i-1}(t) > 0 \}. \qquad (8)$$

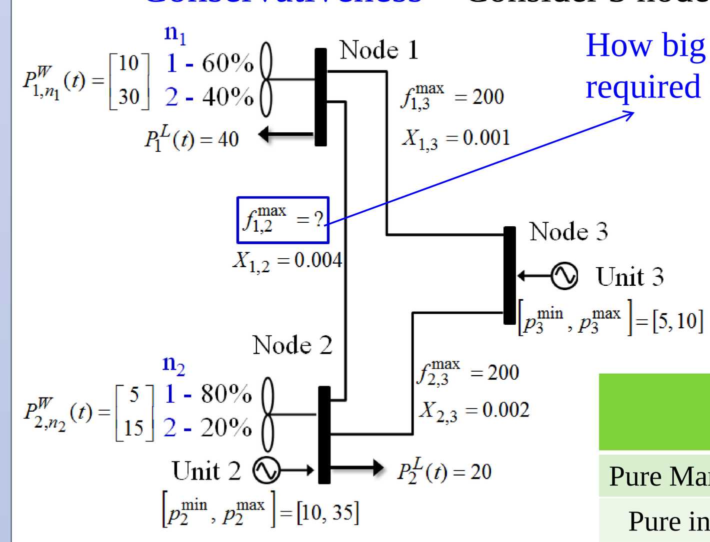
    - *Generalized monotonicity analysis* used to support this conjecture

$$\max_{n_i} P_{i,n_i}^M(t) = P_{i,\max n_i}^M(t), \qquad \min_{n_i} P_{i,n_i}^M(t) = P_{i,\min n_i}^M(t), \forall i, \forall t. \qquad (9)$$

  - Overall problem converted linearly after
    - Including (8) as constraints
    - Substituting the min/max operations with corresponding states
- State transition matrices given and state probabilities pre-computed

Numerical Testing Results

- CPLEX 12.5.1.0 on a PC laptop with an Intel Core(TM) i7-2820QM 2.30GHz CPU and 8GB memory
- Illustrative examples
  - Conservativeness – Consider 3 nodes, 2 wind farms, 2 units, and 1 hour



How big is transmission capacity required for feasible solutions?

	$f_{1,2}^{max}$
Pure Markovian	10
Pure interval	12.86 Conservative!
Our approach	10

	No. of dispatch decisions per unit	No. of flow levels per line
Pure Markovian	10^6	10^6
Pure interval	2+1	2+1
Our approach	10 + 2 + 1	2 + 2 + 1

  - Complexity – Consider 6 wind farms at different buses, 10 states for each
- Solution feasibility and modeling accuracy
  - IEEE 30-bus system with 2 wind farms at 40% wind penetration
    - Free wind curtailment and load shedding at $5,000/MWh penalty
    - Stopping MIP gap 0.1% and then 10,000 Monte Carlo runs
    - Our approach provides 5.23% lower simulation cost than pure interval
    - Our approach is the most accurate, as it has the smallest APE#

Approach		Deter.	Interval	Ours
Optimization	CPU time	2s	53s	1min53s
	Cost (k$)	248.66	280.67	253.40
	Penalty (k$)	0	0.47	0.01
UC cost (k$)		89.46	67.72	65.22
Simulation	E(Cost) (k$)	314.89	263.26	250.17
	APE#	21.03%	6.61%	1.29%
	STD(cost) (k$)	74.46	33.77	35.13
	Penalty (k$)	40.82	0	0

Absolute percentage error (APE) = |optimization cost – simulation cost| / simulation cost × 100%)

- Computational efficiency
  - IEEE 118-bus system with 3 wind farms

		Ours
Optimi-zation	CPU time	41s
	MIP GAP	0.01%
	Cost (k$)	911.48
UC Cost (k$)		12.83
Simula-tion	E(cost) (k$)	920.97
	APE	1.03%
	STD(cost) (k$)	24.64

Conclusion

- An important but difficult issue
- Hybrid Markovian and interval optimization to overcome the complexity caused by transmission constraints
  - Markovian analysis to depend on local state/reduce conservativeness
  - Interval analysis to ensure feasibility against realizations
- Problem transformed into a linear form based on monotonicity, and then solved efficiently by using branch-and-cut
- Opens a new and effective way to address stochastic problems w/o scenario analysis and avoid over-conservativeness

References

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Thank you!